

What is Claimed Is:

1. A perpendicular magnetic recording medium, comprising:
 - (a) a non-magnetic substrate having a surface; and
 - (b) a layer stack formed over said substrate surface, said layer stack comprising, in overlying sequence from said substrate surface:
 - 5 (i) a magnetically soft underlayer;
 - (ii) an interlayer structure for crystallographically orienting a layer of a perpendicular magnetic recording material formed thereon; and
 - (iii) at least one crystallographically oriented magnetically hard
 - 10 perpendicular recording layer;

wherein said magnetically soft underlayer is sputter-deposited at a sufficiently large target-to-substrate spacing and a sufficiently low gas pressure selected to provide said underlayer with a smooth surface having a low average surface roughness Ra below about 0.3 nm, as measured by Atomic Force

15 Microscopy (AFM).

2. The medium according to claim 1, wherein:

said magnetically soft underlayer comprises at least one magnetic material selected from the group consisting of: NiFe (Permalloy), NiFeNb, CoZr, CoZrTa, CoZrCr, CoZrNb, CoFe, Fe, FeN, FeSiAl, FeAlN, FeSiAlN, FeCoC, FeCoB,

5 FeTa₂N, FeTaC, FeCoTaZr, and a laminated structure comprised of a plurality of magnetic layers each comprised of at least one of the recited magnetic materials and spaced-apart by thin spacer layers each comprised of at least one material selected from the group consisting of Ta, C, and Si *or* thin antiferromagnetic coupling layers each comprised of at least one material selected from the group

10 consisting of Ru and IrMn.

3. The medium according to claim 3, wherein:
said magnetically soft underlayer comprises FeCoB.

4. The medium according to claim 1, wherein:
said interlayer structure comprises, in overlying sequence from a surface
of said magnetically soft underlayer:

(1) a first crystalline interlayer of a non-magnetic material formed in a
5 gas atmosphere at a first pressure; and

(2) a second crystalline interlayer of a non-magnetic material formed
in a gas atmosphere at a second pressure greater than said first pressure.

5. The medium as in claim 4, wherein:
said interlayer structure provides said magnetically hard perpendicular
magnetic recording layer formed thereon with a hexagonal close-packed crystal
lattice with a strong $\langle 0002 \rangle$ out-of-plane growth orientation.

6. The medium according to claim 5, wherein:
each of said first and said second crystalline interlayers comprises a non-
magnetic material selected from the group consisting of Ru, RuCr, other Ru-based
alloys, CoCrRu, Ti, CoCr, CoCrPt, CoCrTa, and CoCrMo, and adjacent grains of
5 the second crystalline interlayer are physically separated.

7. The medium according to claim 1, wherein:
adjacent grains of said at least one magnetically hard perpendicular
recording layer are physically separated and said at least one magnetically hard
perpendicular recording layer has a hexagonal close-packed crystal lattice with a
5 strong $\langle 0002 \rangle$ out-of-plane growth orientation.

8. The medium according to claim 7, wherein:
said at least one magnetically hard perpendicular recording layer
comprises at least one magnetic material selected from the group consisting of:

- 5 (1) Co-based magnetic alloys including one or more elements selected from the group consisting of Cr, Fe, Ta, Ni, Mo, Pt, V, Nb, Ge, Si, Al, B, Ti, Zr, Hf, and Pd; (2) oxides of said Co-based magnetic alloys; (3) iron nitrides, and (4) iron oxides.

9. The medium according to claim 1, wherein said layer stack further comprises:

- (iv) an amorphous or crystalline seed layer between said magnetically soft underlayer and said interlayer structure.

10. The medium according to claim 9, wherein:
said amorphous or crystalline seed layer comprises at least one material selected from the group consisting of: Ta, Au, Cu, Pd, TiCr, Pt, and Ag.

11. The medium according to claim 1, wherein said layer stack further comprises:

- (v) an adhesion layer in overlying contact with said substrate surface.

12. The medium according to claim 11, wherein said adhesion layer comprises at least one material selected from the group consisting of: Cr, CrTi, Ti, and TiNb.

13. The medium according to claim 1, wherein said layer stack further comprises:

- (vi) a protective overcoat layer on an outermost surface of said at least one magnetically hard perpendicular recording layer.

14. The medium according to claim 13, wherein said protective overcoat layer comprises a carbon (C)-containing material.

15. A perpendicular magnetic recording medium, comprising:

(a) a non-magnetic substrate having a surface; and
 (b) a layer stack formed over said substrate surface, said layer stack comprising, in overlying sequence from said substrate surface:

- 5 (i) a magnetically soft underlayer;
- (ii) an amorphous or crystalline seed layer;
- (iii) an interlayer structure for crystallographically orienting a layer of a perpendicular magnetic recording material formed thereon; and
- 10 (iv) at least one crystallographically oriented magnetically hard perpendicular recording layer;

wherein:

said magnetically soft underlayer is sputter-deposited at a sufficiently large target-to-substrate spacing and a sufficiently low gas pressure selected to
 15 provide said underlayer with a smooth surface having a low average surface roughness Ra below about 0.3 nm, as measured by Atomic Force Microscopy (AFM); and

said interlayer structure provides said at least one magnetically hard perpendicular magnetic recording layer formed thereon with a hexagonal close-
 20 packed crystal lattice with a strong <0002> out-of-plane growth orientation and comprises, in overlying sequence from a surface of said amorphous or crystalline seed layer:

- (1) a first crystalline interlayer of a non-magnetic material formed in a gas atmosphere at a first pressure; and
- 25 (2) a second crystalline interlayer of a non-magnetic material formed in a gas atmosphere at a second pressure greater than said first pressure.

16. The medium according to claim 15, wherein:

adjacent grains of said second crystalline interlayer and said at least one magnetically hard perpendicular magnetic recording layer are physically separated.

17. The medium according to claim 15, wherein:

said magnetically soft underlayer comprises at least one magnetic material selected from the group consisting of: NiFe (Permalloy), NiFeNb, CoZr, CoZrTa, CoZrCr, CoZrNb, CoFe, Fe, FeN, FeSiAl, FeAlN, FeSiAlN, FeCoC, FeCoB, FeTa₂N, FeTaC, FeCoTaZr, and a laminated structure comprised of a plurality of magnetic layers each comprised of at least one of the recited magnetic materials and spaced-apart by thin spacer layers each comprised of at least one material selected from the group consisting of Ta, C, and Si *or* thin anti-ferromagnetic coupling layers each comprised of at least one material selected from the group consisting of: Ru and IrMn;

said amorphous or crystalline seed layer comprises at least one material selected from the group consisting of: Ta, Au, Cu, Pd, TiCr, Pt, and Ag;

each of said first and said second crystalline interlayers comprises a non-magnetic material selected from the group consisting of Ru, RuCr, other Ru-based alloys, CoCrRu, Ti, CoCr, CoCrPt, CoCrTa, and CoCrMo; and

said at least one magnetically hard perpendicular recording layer comprises at least one magnetic material selected from the group consisting of: (1) Co-based magnetic alloys including one or more elements selected from the group consisting of Cr, Fe, Ta, Ni, Mo, Pt, V, Nb, Ge, Si, Al, B, Ti, Zr, Hf, and Pd; (2) oxides of said Co-based magnetic alloys; (3) iron nitrides, and (4) iron oxides.

18. The medium according to claim 15, wherein said layer stack further comprises:

- (v) an adhesion layer in overlying contact with said substrate surface; and
- (vi) a protective overcoat layer on an outermost surface of said at least one magnetically hard perpendicular recording layer.

19. A method of manufacturing a perpendicular magnetic recording medium, comprising steps of:

- (a) providing a non-magnetic substrate having a surface; and
- (b) forming a layer stack over said substrate surface, said layer stack comprising, in overlying sequence from said substrate surface:
 - (i) a magnetically soft underlayer;
 - (ii) an amorphous or crystalline seed layer;
 - (iii) an interlayer structure for crystallographically orienting a layer of a perpendicular magnetic recording material formed thereon; and
 - (iv) at least one crystallographically oriented magnetically hard perpendicular recording layer;

wherein:

said magnetically soft underlayer is formed by sputter deposition at a sufficiently large target-to-substrate spacing and a sufficiently low gas pressure selected to provide said underlayer with a smooth surface having a low average surface roughness Ra below about 0.3 nm, as measured by Atomic Force Microscopy (AFM); and

said interlayer structure provides said at least one magnetically hard perpendicular magnetic recording layer formed thereon with a hexagonal close-packed crystal lattice with a strong <0002> out-of-plane growth orientation and comprises sputter forming, in overlying sequence from a surface of said amorphous or crystalline seed layer:

- (1) a first crystalline interlayer of a non-magnetic material sputter-deposited in a gas atmosphere at a first pressure; and
- (2) a second crystalline interlayer of a non-magnetic material sputter-deposited in a gas atmosphere at a second pressure greater than said first pressure.

20. The method as in claim 19, wherein:

step (b) comprises forming said second crystalline interlayer and said at least one magnetically hard perpendicular magnetic recording layer such that adjacent grains thereof are physically separated.

21. The method as in claim 19, wherein step (b) comprises forming said layer stack such that:

said magnetically soft underlayer comprises at least one magnetic material selected from the group consisting of: NiFe (Permalloy), NiFeNb, CoZr, CoZrTa, 5 CoZrCr, CoZrNb, CoFe, Fe, FeN, FeSiAl, FeAlN, FeSiAlN, FeCoC, FeCoB, FeTa₂N, FeTaC, and FeCoTaZr, and a laminated structure comprised of a plurality of magnetic layers each comprised of at least one of the recited magnetic materials and spaced-apart by thin spacer layers each comprised of at least one material selected from the group consisting of Ta, C, and Si *or* thin anti-ferromagnetic coupling (AFC) layers each comprised of at least one material 10 selected from the group consisting of Ru and IrMn;

said amorphous or crystalline seed layer comprises at least one material selected from the group consisting of: Ta, Au, Cu, Pd, TiCr, Pt, and Ag;

each of said first and said second crystalline interlayers comprises a non- 15 magnetic material selected from the group consisting of Ru, RuCr, other Ru-based alloys, CoCrRu, Ti, CoCr, CoCrPt, CoCrTa, and CoCrMo; and

said at least one magnetically hard perpendicular recording layer comprises at least one magnetic material selected from the group consisting of: (1) Co-based magnetic alloys including one or more elements selected from the 20 group consisting of Cr, Fe, Ta, Ni, Mo, Pt, V, Nb, Ge, Si, Al, B, Ti, Zr, Hf, and Pd; (2) oxides of said Co-based magnetic alloys; (3) iron nitrides; (4) and iron oxides.

22. The method as in claim 19, wherein step (b) further comprises forming as part of said layer stack:

- (v) an adhesion layer in overlying contact with said substrate surface; and
- 5 (vi) a protective overcoat layer on an outermost surface of said at least one magnetically hard perpendicular recording layer.